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The effect of climate change on agro-climatic indicators in the UK

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Abstract

The effect of climate change on agriculture in the UK is here assessed using a comprehensive series of policy-relevant agro-climate indicators characterising changes to climate resources and hazards affecting productivity and operations. This paper presents projections of these indicators across the UK with gridded observed data and UKCP18 climate projections representing a range of greenhouse gas emissions scenarios. The projections can be used to inform climate change mitigation and adaptation policy. There will be substantial changes in the climate resource and hazard across the UK during the twenty-first century if emissions continue to follow a high trajectory, and there will still be some changes if emissions reduce to achieve international climate policy targets. Growing seasons for certain crops will lengthen, crop growth will be accelerated, and both drought and heat risks (for some types of production) will increase. Soils will become drier in autumn, although there will be less change in winter and spring. The longer growing seasons and warmer temperatures provide opportunities for new crops, subject to the effects of increasing challenges to production. Most of the changes are relatively consistent across the UK, although drought risk and heat stress risk increase most rapidly in the south and east. The climate change trend is superimposed onto considerable year to year variability. Although there is strong consensus across climate projections on the direction of change, there is considerable uncertainty in the rate and magnitude of change for a given emissions scenario. For the temperature-based indicators, this reflects uncertainty in climate sensitivity, whilst for the precipitation-based indicators largely reflects uncertainty in projected changes in the weather systems affecting the UK.

Keywords Climate impacts · Agriculture · UKCP18 · Drought · Heat impacts

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1 Introduction

In August 2020, the *Times* newspaper published a news article entitled 'Climate forces farms to start growing soya'. A wet winter and dry summer had led to 'the worst wheat harvest in decades', but some farmers had begun growing soya, a crop which needs higher temperatures than typically expected in the UK. This encapsulates the potential effect of climate change on agriculture in the UK: changes in the potential for crop and livestock production, but changes too in the likelihood of challenging weather events affecting both operations and crop growth.

Agricultural land covers 72% of the UK (Defra 2020a), divided almost equally between cropland (wheat and barley being the most common crops), improved pasture and rough grazing. The agri-food sector as a whole employs 3.6 million people and contributes around 6% to the UK's GVA, although the agricultural sector itself contributes less than 1% of the UK's GDP and directly employs around 476 thousand people (Defra 2020a). The Second UK Climate Change Risk Assessment (CCRA2) highlighted the sensitivity of UK agriculture to climate change (Brown et al. 2016), potentially affecting not only agricultural production and businesses but also the management, biodiversity, and cultural value of landscapes across large parts of the UK.

Climate change due to an increasing concentration of greenhouse gases has three broad effects on crop and livestock productivity (see also Olesen and Bindi 2002; Deryng et al. 2014; Trnka et al. 2014; Gobin 2018). First, the climate regime at a place (its mean and variability) affects what could or could not be grown and what measures are needed—such as irrigation—to support production: this can be seen as the climate resource (Stehr and von Storch 2009; Selvaraju et al. 2011). A change in climate regime potentially alters these climate resources, making some types of production less viable but enabling others. Meanwhile, increases in atmospheric carbon dioxide concentrations can lead to increased productivity of some crops (including grass, wheat, and barley), but changes in climate may adversely affect soil nutrients and fertility and weed growth will also be affected. Changes to climate regime will potentially therefore affect farmer decisions on what to produce and what infrastructure is needed to support that production. What the farmer actually plants or produces, however, is also influenced by agro-economic policy, national and international food markets, and anticipated prices.

Second, extreme events during the growing season can result in reduced or lost production. For example, drought or high temperatures at critical times can stress crops and livestock. Flooding, heavy rain, and hail (currently rare in the UK) can damage crops. High temperatures accelerate crop growth and development stages, potentially leading to lower yields (Craufurd and Wheeler 2008). Outbreaks of pests, parasites, and diseases may be triggered or facilitated by weather conditions.

Third, weather may affect operations such as access to fields, planting, and harvesting. For example, prolonged wet conditions in winter and spring may prevent farmers from accessing land with machinery or moving livestock into fields from winter accommodation.

In principle, it is possible to estimate the effects of climate change on crop and livestock production by modelling all these drivers. However, this is not only computationally difficult (for example, it would be necessary to construct and apply models for all potential crops and livestock systems) but also conceptually challenging because farmer decisions may determine the impacts of climate change. These farmer decisions will be based partly on perceptions of changing conditions on the farm, but partly on national and international markets and policy changes, and on the dissemination of innovation. An alternative approach is therefore to characterise the potential effects of climate change on agriculture through a suite of climate-based indicators ('agro-climate indicators'; Trnka et al. 2010; Hatfield et al. 2020; Walsh et al. 2020). Such indicators are proxies for the effects of weather and climate on specific

agricultural activities, but do not directly quantify themselves effects on, for example, productivity, animal welfare, or specific agricultural operations.

This paper presents a series of agro-climatic indicators which characterise the potential effects of climate change on agriculture in the UK. The indicators are taken from the literature (Knox et al. 2010; Rivington et al. 2013; Harding et al. 2015; Parsons et al. 2019; Bachmair et al. 2018; Dunn et al. 2014; Jones et al. 2020), are relevant to stakeholders (e.g. Matthews et al. 2008), and are directly linked to weather impacts. They cover changes to the climate resource, climate hazard, and agricultural operations, for both food and forage crops and livestock. They are calculated across the UK, using a consistent set of observed climate data and UKCP18 climate projections (Lowe et al. 2018). The paper calculates 'worst case' projections under high emissions and considers the effects of international efforts to reduce greenhouse gas emissions, and shows the variations in impact across the UK. It is designed to inform strategic level assessments of the effect of climate change on agriculture in the UK, both to support the development of high-level climate policy and to support strategies to enhance adaptation and resilience in the agriculture sector. The paper presents results produced as part of a broader multi-sectoral evaluation of policy-relevant indicators of climate change in the UK (Arnell et al. 2021). CCRA2 concluded that more research was needed into the nature and scale of changing land suitability and its impacts (Brown et al. 2016): this paper addresses this gap.

Section 2 describes the agro-climate indicators used in this study, together with the climate projections. Section 3 presents, for context, the current (1981–2010) geographical distribution of these indicators. Changes in the indicators by region and nation with high emissions and the effects of reductions in emissions are presented in Section 4. Section 5 discusses implications for UK agriculture and draws some general conclusions.

There have so far been few published UK-scale general analyses of the effect of climate change on agricultural systems. Harding et al. (2015) calculated five agro-climate indicators across the UK, and Fezzi et al. (2014) used an empirical econometric model with growing season temperature and precipitation to estimate change in the relative distributions of grassland and cereal crops across the UK: Ritchie et al. (2019) applied the same model with different climate scenarios across Great Britain. Rivington et al. (2013) calculated indicators across Scotland. Warmer temperatures would suggest an increase in the proportion of agricultural land in England and Wales (Keay et al. 2013) and Scotland (Brown et al. 2011) in the highest land capability class, but that this would be more than offset by reductions in capability due to increased drought. Other national-scale studies have looked at specific crops (including wheat (Semenov 2009; Cho et al. 2012; Harkness et al. 2020), grassland (Qi et al. 2018), barley (Yawson et al. 2016), and potatoes (Daccache et al. 2012)) or livestock systems (Dunn et al. 2014; Fodor et al. 2018). Taken together, these studies project an increase in growing season length and growing degree days, an increase in potential productivity for wheat, barley, and for grassland—primarily due to an increase in atmospheric CO_2 concentrations—but increasing effects of summer drought on wheat and potato (and by implication other seasonal vegetables) and increasing heat stress for livestock.

2 Agro-climate indicators, data, and climate projections

2.1 Overall approach

The effect of climate change on agriculture in the UK is characterised by a series of agro-climate indicators, using 12×12-km gridded observed daily climate data for 1981–2010 and

UKCP18 climate projections applied using the delta method. Results are aggregated to the regional level (Fig. 1), weighted by area of agricultural land.

Fig. 1 UK regions

2.2 Agro-climate indicators

Table 1 summarises the agro-climate indicators used here, separated into indicators characterising the climate resource, agricultural operations, and climate hazards—although the boundaries between the three categories are not sharp. The indicators are described in more detail in Supplementary Material. All are calculated from daily weather data to produce time series of annual totals or accumulations.

The thermal growing season starts when average temperatures exceed 5.6 °C, and growing season length is the time from the start of the thermal growing season to when average temperatures fall below 5.6 °C. Plant phenological development is, in the absence of other constraints on water and nutrient availability, determined by accumulated temperature above 5.6 °C as measured by growing degree days. This may be restricted on days with high temperature, but no upper limit is imposed here, and this analysis uses the same algorithm for calculating growing degree days as used by Kendon et al. (2019a). The productivity of perennial crops—such as grassland—is directly linked to growing degree days, in the absence

Table 1 Summary of the agri-climate indicators

Indicator	Definition	Reference
Climate resource		
Start of growing season	The first of five consecutive days with average temperature >5.6 °C (day of year)	Rivington et al. (2013) Harding et al. (2015)
Growing season length	Days between start of growing season and first of five consecutive days with average temperature <5.6 °C (days)	Rivington et al. (2013) Harding et al. (2015)
Growing degree days	Sum of average temperatures above 5.6 °C (°C-days)	Rivington et al. (2013)
Potential soil moisture deficit	Annual maximum potential soil moisture deficit, calculated from potential evaporation minus precipitation	Knox et al. (2010) Daccache et al. (2012)
Agricultural operations		
Start of field operations	Day when accumulated average temperature from January 1st exceeds 200 °C (day of year)	Rivington et al. (2013) Harding et al. (2015)
Wet soils	Days with soil moisture at or above field capacity (days/year)	
Climate hazard		
SPEI severe drought	Time with 6-month Standardised Precipitation Evaporation Index < −1.5 (proportion of time)	Parsons et al. (2019)
SPI severe drought	Time with 3-month Standardised Precipitation Index < −1.5 (proportion of time)	Bachmair et al. (2018)
Crop growth duration	Days to accumulate reference period Growing Degree Days (days)	
Frost days	Days with minimum temperature <0 °C (days/year)	Rivington et al. (2013)
Accumulated frost	Sum of minimum temperatures below 0 °C (°C-days)	Rivington et al. (2013) Harding et al. (2015)
Parasite outbreaks in sheep	Days with average temperature >9 °C (indent for consistency with other items in this column) (days/year)	Jones et al. (2020)
Heat stress effect on milk yield	Days with temperature humidity index >70 (days/year)	Dunn et al. (2014)
Heat stress during wheat anthesis	Days with maximum temperature>32 °C between 1 May and 15 June (days/year)	Jones et al. (2020)

of other constraints on growth. The total number of growing degree days influences which annual crops could feasibly be planted. The potential soil moisture deficit (PSMD) is a measure of crop demand for water and hence the potential need for supplemental irrigation. It is calculated as the largest cumulative difference during the year between potential evaporation and rainfall (Knox et al. 2010; Daccache et al. 2012). The climatic suitability of land for agriculture is often based on accumulated temperature and PSMD (e.g. Brown et al. 2011; Daccache et al. 2012; Keay et al. 2013).

The start of field operations indicator is a proxy for the earliest date in the year when a field might be usefully worked (Harding et al. 2015): an accumulated thermal sum of 200 °C (Tsum200) is commonly used by farmers as a rule of thumb for when to apply fertiliser to grass, for example. If soils are wet, then farmers cannot use machinery or put livestock into fields. This is characterised here by the number of days when soil moisture is at or above field capacity, calculated using a simple daily water balance model assuming a constant well-drained clay-loam soil with fixed field capacity across the UK (see Supplementary Material for a sensitivity analysis for other soil properties). Again, this informs the capability of land for agriculture (Keay et al. 2013).

Farmer decisions on what and when to plant are influenced by anticipated climate resource and operational conditions, and perceptions of the chance of damaging events. Once decisions are made, the productivity of crops and livestock will depend on actual growing conditions and the occurrence of damaging events. Lack of water is characterised by two drought indicators. The Standardised Precipitation Index (SPI; McKee et al. 1993) is based on precipitation totals accumulated over 3 months (SPI-3), following Bachmair et al. (2018). The Standardised Precipitation Evaporation Index (SPEI; Vicente-Serrano et al. 2010) is based on the difference between precipitation and potential evaporation accumulated over 6 months (SPEI-6), following Parsons et al. (2019). Both indicators are calculated by standardising the accumulated time series over a specific reference period, here 1981–2010, and critical thresholds determined empirically rather than using a fitted theoretical distribution. In each case, the indicator is the proportion of time with an index value below a threshold value of −1.5, which occurs by definition 6.7% of the time over the reference period (or for 24 out of the 360 months). Both drought indicators are associated with agricultural impacts in the UK (Haro-Monteagudo et al. 2017; Bachmair et al. 2018; Parsons et al. 2019).

High temperatures can limit growth (and at the extreme kill plants) and cause discomfort to livestock, but the critical thresholds vary between crops and animals and vary through the year. Two illustrative heat-stress indicators are calculated here. One is the number of days during the anthesis (flowering and seed setting) stage for wheat when maximum temperature exceeds 32 °C (Jones et al. 2020): anthesis is assumed to occur between 1 May and 15 June. Grain yield reduces by at least 10% for each day during anthesis that temperature exceeds 32 °C. The other characterises the effect of high temperatures on dairy cattle milk yield (Dunn et al. 2014; Fodor et al. 2018; Jones et al. 2020). Here, this is represented by the number of days the temperature humidity index (THI) exceeds 70. THI is calculated from daily average temperature and relative humidity. Milk yield falls linearly with increase in THI above 70 (which is equivalent to an average temperature of around 21 °C with a typical relative humidity of 75%). At the other extreme, cold days can hinder growth—although some crops (such as apples) require periods of low temperatures at critical development stages. The number of cold days is here characterised by the number of days with minimum temperatures below 0 °C (air frost).

Annual crops need to accumulate specific numbers of degree days to reach specific growth stages, but if these stages are reached too quickly, then yields are reduced (Craufurd &

Wheeler & 2008; Hatfield et al. 2011). This is characterised here by the time taken in a year to accumulate the average reference period (1981–2010) growing degree days: a reduction in crop growth duration implies a reduction in yield compared to the average expectation.

Finally, productivity can be affected by pests, parasites, and disease. The accumulated frost indicator measures the severity of winter and is a proxy for the likelihood that pests survive over winter (Harding et al. 2015): the more negative the indicator, the lower the likelihood that pests survive. It is specifically based on data from aphids affecting cereal crops (Dewar and Carter 1984). A second indicator characterises parasite outbreaks in sheep (Jones et al. 2020). The number of days with average temperature above 9 °C is an indicator of the potential number of life cycles of one of the most significant gastro-intestinal parasites (*Haemonchus contortus*) causing ill-health and malnourishment in sheep (Jones et al. 2020).

Climate change will affect the mean and the year-to-year variability in these indicators. Different agricultural stakeholders will have different priorities for information on how the indicators will change. Some may be interested in projected changes in the mean, whilst others might be more concerned by changes in the chance of experiencing some critical event or season. Some want to get an idea of the general direction and significance of climate change, and others are more concerned about planning to enhance resilience. There are therefore several different ways of presenting how climate change will affect agro-climate indicators, and some involve defining critical thresholds representing a 'significant' change. The analysis here is primarily concerned with characterising the potential effects of climate change at a strategic level, and in itself is not intended to directly inform specific farm or industry adaptation actions to enhance resilience. With one exception, the analysis is therefore based on changes to long-term (30 years) mean values in the indicators, recognising both that any individual year may experience a value very different to the mean, and that changes in the mean may be small compared with year-to-year variability. The one exception is the wheat heat stress indicator, which is expressed as the chance of experiencing at least one heat stress day in a year. This is because heat stress days are very infrequent, the average annual number is not very meaningful, and the critical threshold is very clear (just 1 day above the threshold causes problems). For all the other indicators, thresholds defining critical change depend on context or degree of risk aversion.

The set of indicators presented here characterise many of the effects of weather and its variability on crop and livestock productivity. Other potential effects are not considered. These include the occurrence of late frosts, the effect of short-duration heavy rainfall on crops, the effects of river flooding, and the effect of hailstorms. The indicators also do not consider the effects of climate change on soil fertility or erosion, or the potential beneficial effects of increasing CO_2 concentrations.

2.3 Reference climate data

Observed climate data were taken from HadUK-Grid 12-km resolution observational data set (Met Office 2018; Hollis et al. 2019), supplemented by ERA5 reanalysis (Copernicus Climate Change Service 2017). The HadUK-Grid 12 km data set includes daily minimum and maximum temperature and rainfall up to 2018, but sunshine hours, windspeed, and relative humidity (needed to estimate potential evaporation) are only available as monthly averages. Daily windspeed and relative humidity was therefore estimated from the ERA5 reanalysis, rescaling the ERA5 reanalysis so that the monthly mean equalled the HadUK-Grid monthly mean. The time period 1981–2010 is used to represent current climate.

2.4 Climate projections and their application

The UKCP18 land climate projections (Lowe et al. 2018; Murphy et al. 2019) consist of four strands: global, regional, local, and probabilistic. The global strand comprises an ensemble of 15 climate projections at a spatial resolution of 60×60km made using variants of the HadGEM3 climate model and an ensemble of 12 projections made using CMIP5 climate models. Projections are made for two levels of climate forcing, representing high (RCP8.5) and low (RCP2.6) emissions. These projections each maintain realistic physical relationships between climate variables and coherent patterns of change across the UK. The regional strand is based on higher-resolution versions of HadGEM3, and in practice gives similar results to the global HadGEM3 projections. The local strand is a smaller number of even higher-resolution projections, and these were not applied. The probabilistic strand consists of an ensemble of 3000 equally plausible projections at four different levels of forcing, but these do not necessarily maintain realistic physical relationships between variables as represented by the global and regional models.

This paper focuses on the probabilistic projections with RCP2.6, RCP6.0, and RCP8.5 forcings, which have the global temperature increases summarised in Table 2. The indicators were also calculated with the global and regional strands, and are presented in Supplementary Material: important differences between these strands and the probabilistic strands are highlighted below.

Figure 2 shows regional average changes in seasonal temperature and rainfall with the three sets of forcings. Temperature increases in each season consistently across the UK. Rainfall tends to decrease in summer, particularly across the south and east, and increase in autumn and winter, particularly in the north and west. The direction of change in rainfall in spring is more uncertain. The changes are greatest with the higher emissions.

The climate projections to 2100 for monthly average temperature, precipitation, vapour pressure, cloud cover, and windspeed were applied to the gridded observed 1981–2010 daily time series using the delta method (see Supplementary Material). Each variable for a given ensemble member was first expressed as an anomaly from its 1981–2010 monthly mean (absolute for temperature, relative for the other variables). The individual probabilistic strand ensemble members do not necessarily have consistent changes in minimum and maximum temperatures, so changes in average temperature were applied to both minimum and maximum temperatures. The probabilistic projections also do not include windspeed, so this was assumed unchanged (this is only used in the calculation of potential evaporation, and leaving this unchanged has very little effect on changes in potential evaporation).

Table 2 Increases in global mean temperature with the RCP2.6, RCP6.0, and RCP8.5 projections

| | Increase in temperature above pre-industrial levels (°C) | | |
	RCP2.6	RCP6.0	RCP8.5
2050s	1.6 (1.1–2.2)	1.7 (1.3–2.2)	2.3 (1.7–2.9)
2100	1.9 (1.3–2.6)	3.7 (2.8–4.7)	5.1 (4.0–6.5)

The table shows the median estimate of increase in global mean temperature, with the 10th to 90th percentile range in brackets. The average global temperature over the period 1981–2010 was approximately 0.61 °C warmer than pre-industrial levels
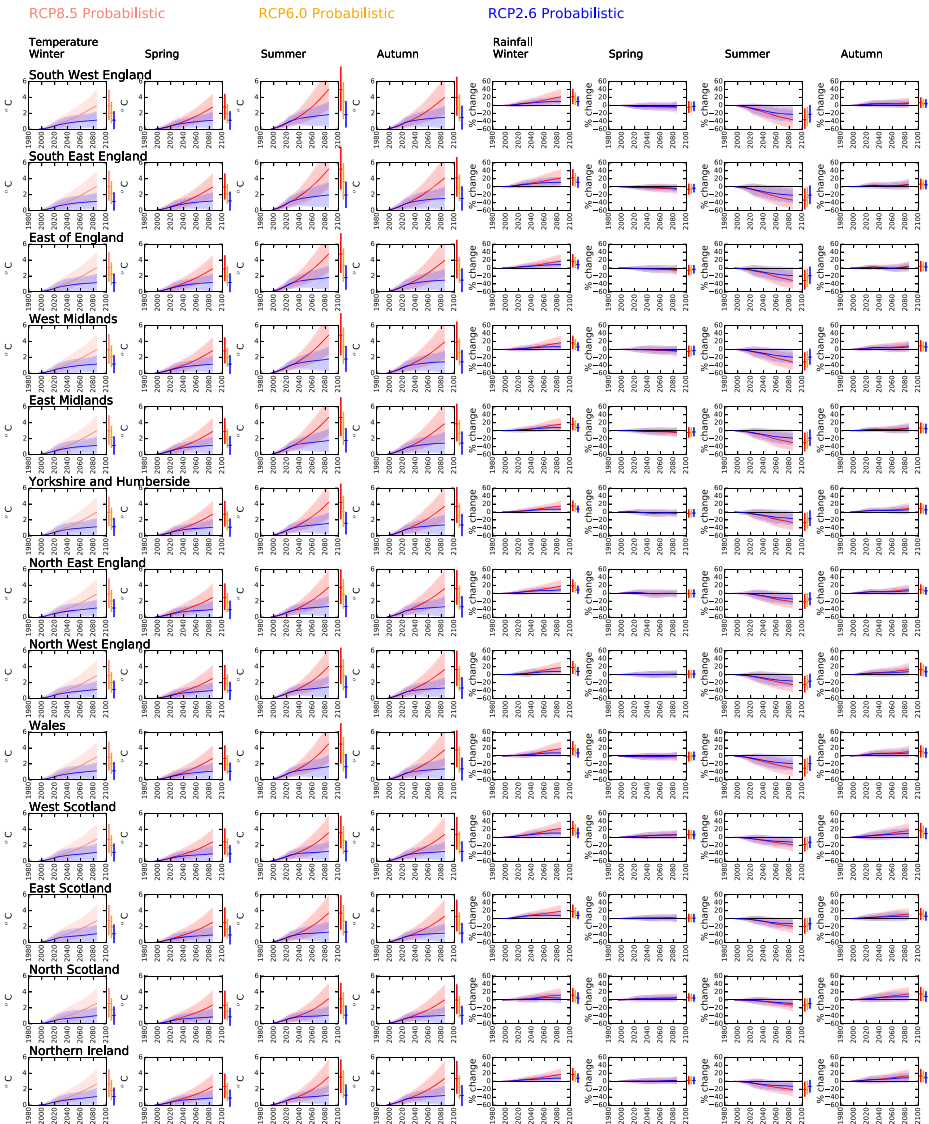
Fig. 2 Change in 30-year mean seasonal temperature and precipitation by region: UKCP18 probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The mean values are plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high'). The bars on the right show the 2071–2100 mean

The resulting time series of monthly anomalies were then smoothed using a 31-year running mean to remove the effect of year-to-year variability and extract the climate change signal. In order to calculate anomalies for the last 15 years of the projections, the anomaly time series were extrapolated using linear regression. There can be large differences in anomaly from 1 month to the next—which introduces unrealistic steps at month boundaries—so the monthly anomalies were interpolated to the daily scale before being applied to the observed daily data. Time series of daily weather from 2011 to 2100 were constructed by repeating the 1981–2010 time series three times and applying the annual time series of anomalies.

The UKCP18 projections comprise ensembles of projected time series of monthly or daily weather variables. These model time series include changes in both mean and variability, as simulated by the climate model, and could in principle be used directly to calculate the agro-climate indicators. Instead, this study uses the delta method as outlined above for three reasons. First, observed data is used to characterise the current climate because this observed experience is familiar to stakeholders. Second, some form of bias adjustment need to be applied to the UKCP18 model projections. Different bias adjustment approaches exist correcting for different aspects of bias, and all assume that the adjustments continue into the future. Third, it would have been impractical to test and apply bias adjustment methods which preserved relationships between variables for all projections and locations.

The delta method as applied here produces time series of daily weather which broadly maintain observed patterns of day to day and year to year variability. However, it assumes that relative variability in climate from year to year does not change into the future, and that the proportional change in a variable does not vary with the magnitude of that variable. Climate change could generate increased variability in summer temperatures from year to year (Kendon et al. 2019b), and this would increase the number of high temperature extremes. Similarly, a reduction in the number of wet days would increase the chance of prolonged dry spells, and an increase in the number of heavy precipitation events (Kendon et al. 2019a) could lead to an increase in short-duration soil water-logging. These potential effects are not incorporated here.

2.5 Regional averages

The agro-climate indicators are implemented at a spatial resolution of 12×12km across the UK. Regional averages are calculated for UK regions (8 in England (excluding London), 3 in Scotland, and Wales and Northern Ireland), weighting the grid cell values by the area of cropland and improved pasture taken from the 2015 UK Land Cover Map (CEH 2017). The PSMD and wheat heat stress indicators are weighted by cropland area only, and the livestock indicators were averaged over the area of improved pasture.

3 Current values of the agro-climate indicators

Figure 3 shows the geographical distribution of the resource, operational, and hazard agro-climate indicators with the observed 1981–2010 climate (except for the two drought indicators, which are by definition constant across the UK over the reference period, and the crop growth duration which is equal to the growing season length over the reference period). All maps show the average (or chance) calculated over the 30-year period.

The spatial patterns largely reflect the variation in temperature across the UK. At present, the growing season typically starts in early March in southern England and by late April in upland areas. The growing season varies from over 250 days in the south to less than 200 in the uplands and parts of the north. Average annual maximum potential soil moisture deficit is greatest in the south and east.

The start of field operations is between mid-February and mid-March in southern England, and up to a month later in the uplands. The average number of days with soil moisture above field capacity (assuming here a clay-loam soil) ranges from less than 20 in eastern England to over 200 in parts of Scotland. South east England has around 50 frost days a year, and this

Observed 1981-2010
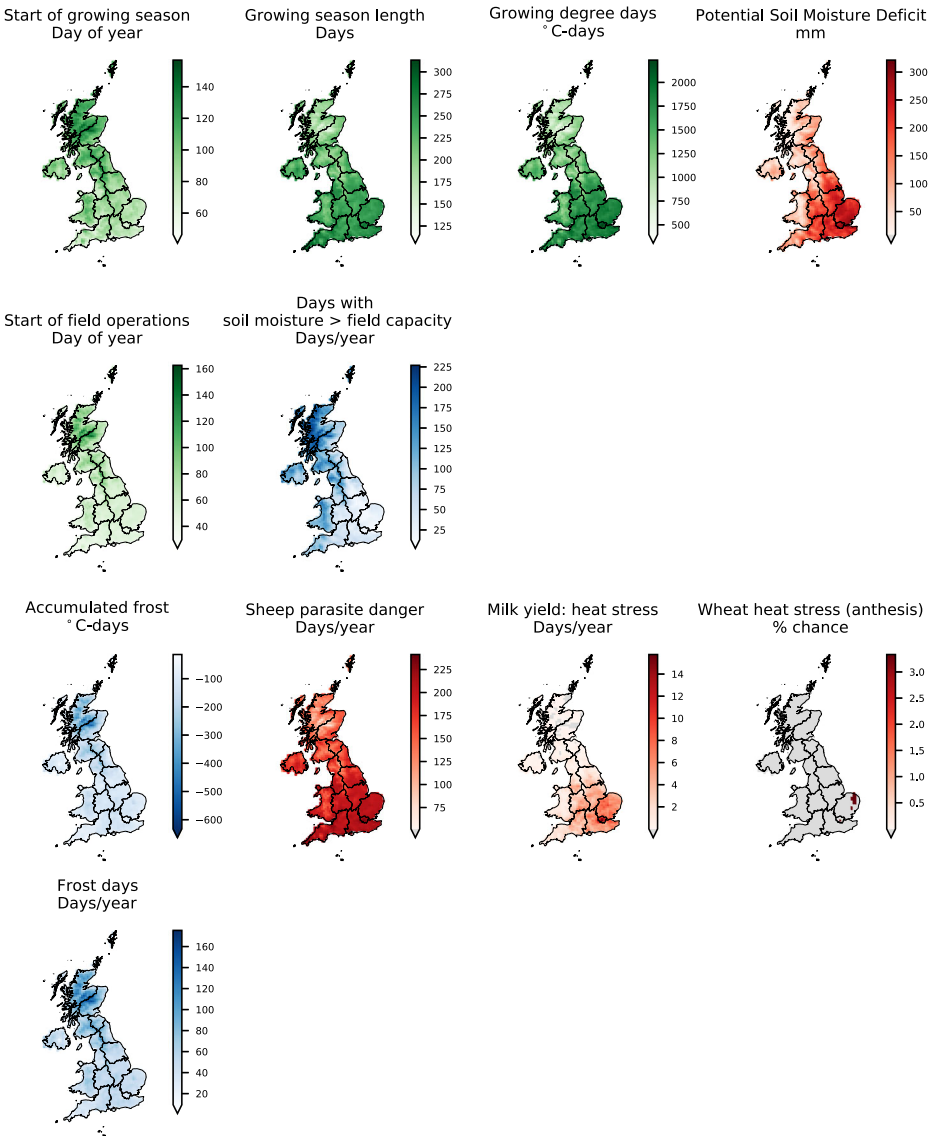
Fig. 3 The reference period (1981–2010) distribution of agro-climate indicators across the UK. The maps show the 30-year mean, and for the wheat heat stress indicator, the percentage of years between 1981 and 2010 with at least one heat stress day

increases to over 70 in the uplands. More than 200 days per year are suitable for sheep parasites in south east England, falling to under 150 in upland areas in the north and west. There were on average fewer than 3 or 4 days with potential heat-related reductions in milk yield in south and east England, and far fewer in the west and north. Over the period 1981–2010, days with damaging high temperatures for wheat occurred just in 1996 in eastern England.
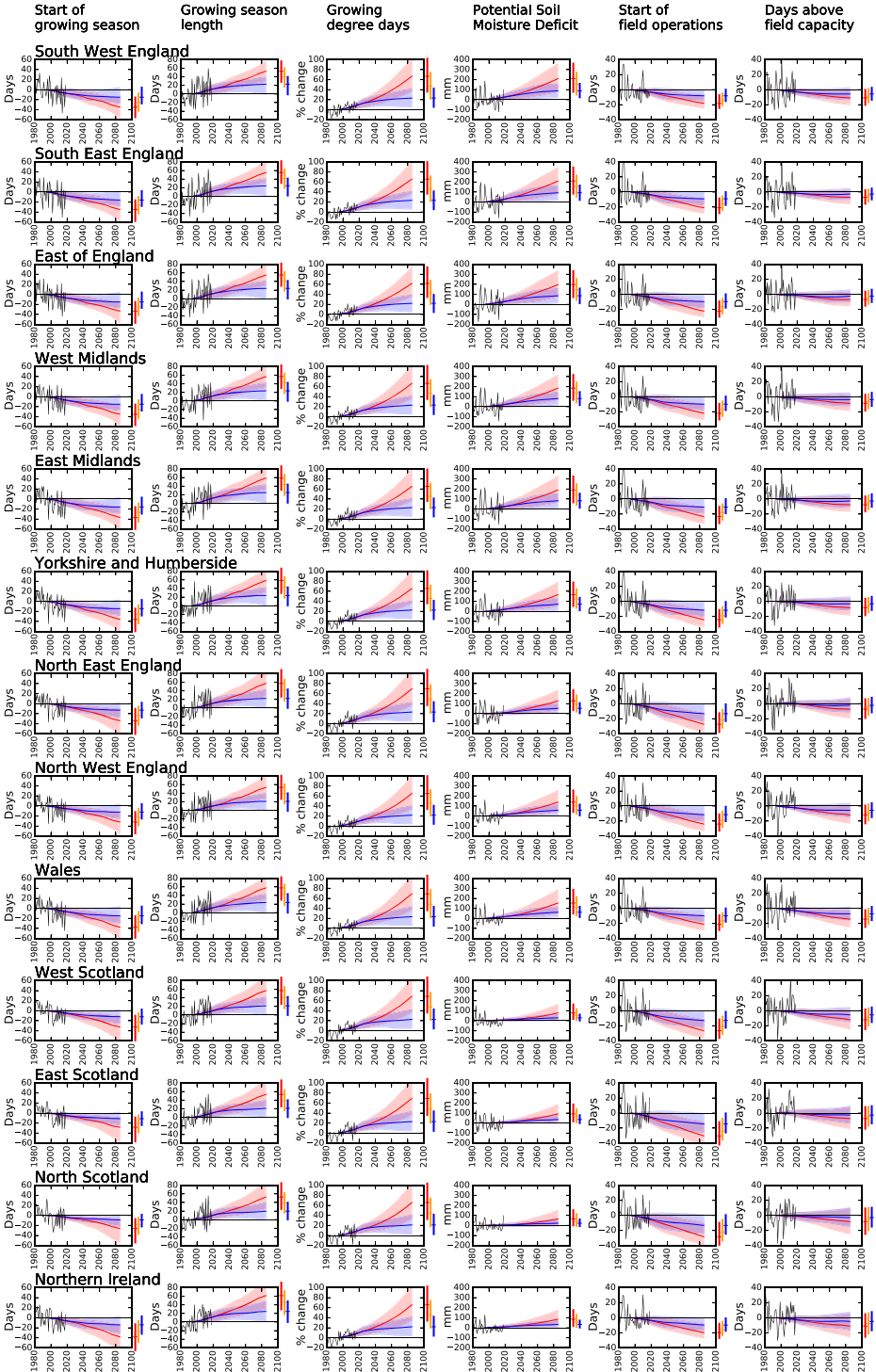
Fig. 4   Indicators of climate resource by region: probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The 30-year mean values are plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high'). Annual values from observed data between 1981 and 2018 are shown in black

4 Change in agro-climate indicators through the twenty-first century

Figures 4 and 5 show the regional average agro-climate resource, operational, and hazard indicators through the twenty-first century with the three emissions scenarios (data provided in
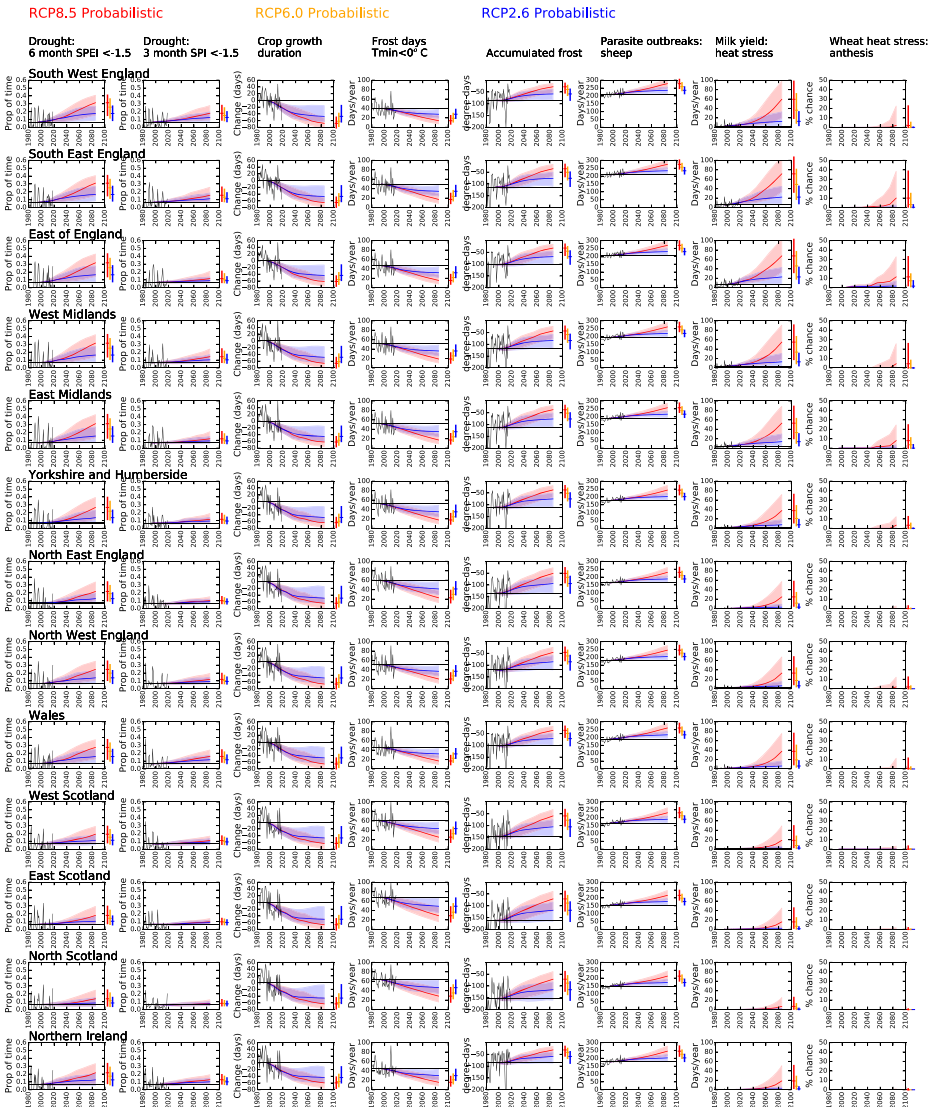

Fig. 5   Indicators of climate hazard by region: probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The 30-year mean values are plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high'). Annual values from observed data between 1981 and 2018 are shown in black

Supplementary Material). The plots show the 30-year means with the UKCP18 projections and, with the exception of the wheat heat stress indicator, annual values for the period 1981 to 2018 calculated from the HadUK-Grid observations. The shaded areas for each projection represent the effects of uncertainty in the change in climate for that forcing: values for individual years will of course be outside this uncertainty range. The plots show the effect of climate change on the mean, and a comparison between the observed annual values and projections for change in the mean give an indication of the future occurrence of 'extreme' years. The plots for the resource and operational indicators (Fig. 4) show change relative to the 1981–2010 mean, whilst the hazard indicators (with the exception of crop growth duration) show absolute values (Fig. 5).

The pattern of variability in each indicator across the UK is illustrated in Fig. 6, which shows the median estimate of the indicators averaged over the period 2071–2100 with the high RCP8.5 emissions (similar maps for 2041–2070 are presented in Supplementary Material). Figure 7 and Table 3 show the average indicators for the four nations of the UK.

Together, the plots show substantial changes in most of the agro-climate indicators across the UK. Changes are smaller with the lowest RCP2.6 emissions, but even here, there will be agriculturally relevant changes to climate. To the 2040s at least, there is little difference between the three emissions scenarios. For most of the indicators, year-to-year variability is large compared with the climate change trend in the mean.

With the highest emissions, the start of the growing season is brought forward by between 30 and 50 days by the 2080s in southern England—a change of approximately 3 to 5 days per decade. The rate of change is slightly greater in northern England and Scotland. The growing season would be between 40 and 80 days longer by the 2080s, an increase of 4–8 days per decade. Growing degree days increase by between 4 and 10% per decade, meaning that they could double by the 2080s. For all three of these indicators, the observed trend over the period 1981 to 2018 is broadly consistent with the climate change trend (and the observed trend in growing degree days is the same as in Kendon et al. 2019b).

The potential soil moisture deficit increases very substantially across the UK. The date for the start of field operations (Tsum200) is between 8 and 20 days earlier in the south by the 2080s, and 10 to 40 days earlier in the north. The number of days with soils at field capacity decreases through the twenty-first century, primarily due to soils being drier for later into autumn (Rivington et al. 2013; see also Supplementary Material). This is despite the projected general increase in autumn rainfall (Fig. 2), and occurs because greater evaporation means soil moisture deficits persist for longer into autumn. The greatest absolute change is in upland regions (typically unimproved grassland) where potential evaporation in late spring and early autumn is currently similar to rainfall: higher potential evaporation and lower rainfall therefore increases soil moisture deficits considerably. The detailed projected changes in days with wet soils vary with soil type (Supplementary Material). The reduction in wet soil days in autumn and annually is less with sandy soils and shallow soils. For these three indicators, there is little apparent trend in the observations.

Drought frequency (expressed as the proportion of time in drought) increases across the whole of the UK, with the greatest increases in the south. The increase in drought frequency is greater with the SPEI indicator because this incorporates the effect of increased potential evaporation, and by the 2080s, severe drought conditions could occur around 30% of the time compared with 6.7% now. Crop growth duration (the time to accumulate reference period growing degree days) decreases across the UK, but the rate of change slows after the 2050s: this trend is consistent with the observations. The number of days with air frost decreases
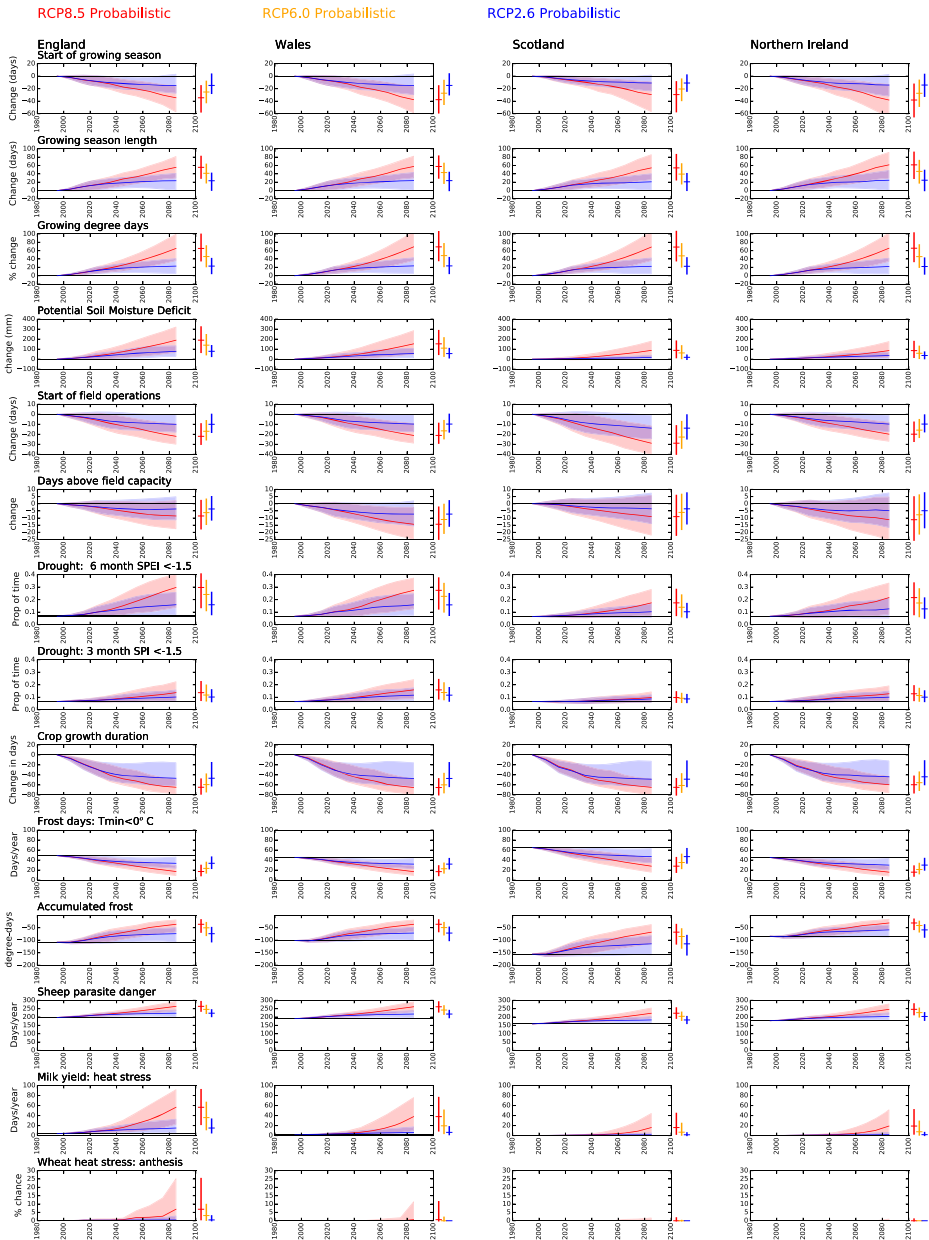
Median of Probabilistic RCP8.5 projections 2071-2100
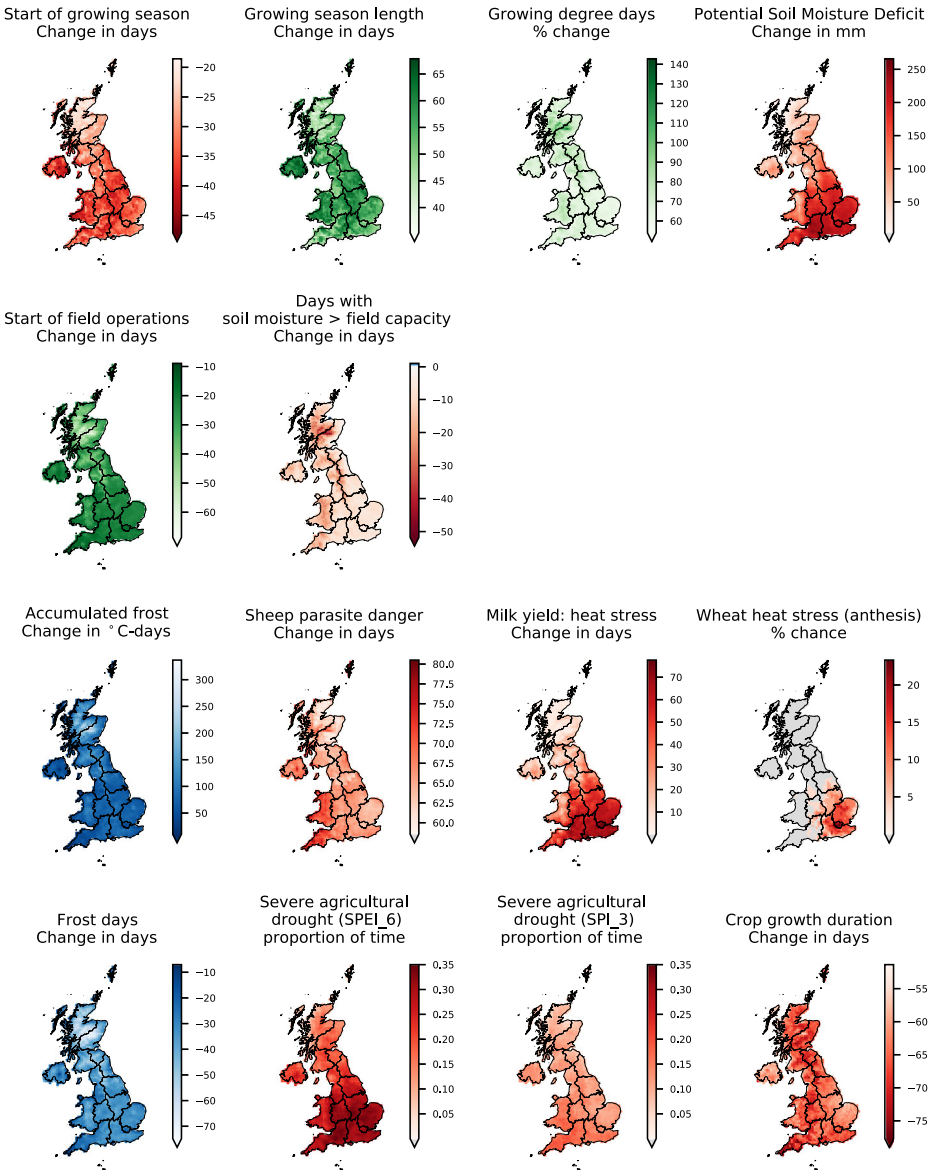
Fig. 6 Variation in agro-climate indicators across the UK with high (RCP8.5) emissions over the period 2071–2100: median of the probabilistic projections. The maps show the 30-year mean indicator (% chance over 30 years for the wheat heat stress indicator)

significantly through the century, again consistent with observations. Accumulated frost reduces meaning an increased risk that pests can survive winter, and in southern England may be almost eliminated by the end of the century. The number of days with temperatures suitable for sheep parasites increases across the UK, by up to 35 days by the 2050s: the greatest increase is in Wales and the west and south of England. There is a very large increase in the

Fig. 7 Indicators of agri-climate hazard and resource: national scale: probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The mean values are plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high')

number of days causing heat stress for dairy cattle across southern England, particularly with high emissions. This increase is proportionally greater than for the sheep parasite indicator because the effective temperature threshold is much higher. Finally, extreme temperatures during wheat anthesis remain extremely rare until the 2050s (consistent with Harkness et al.

Table 3 National-scale agro-climate indicators: RCP2.6 and RCP8.5. The table shows the 1981–2010 mean value, together with the median, low, and high estimates for the 2050s and the 2080s

| | | 1981–2010 | RCP2.6 | | | | | | RCP8.5 | | | | | |
| | | | 2050s | | | 2080s | | | 2050s | | | 2080s | | |
			Median	Low	High	Median	Low	High	Median	Low	High	Median	Low	High
England														
Start of growing season	Day	83	70	61	81	68	56	86	63	52	76	49	26	68
Growing season length	Days	247	268	254	281	271	248	288	280	264	296	303	277	329
Growing degree days	°C-days	1710	2050	1841	2264	2102	1802	2408	2284	2006	2586	2825	2323	3403
Potential soil moisture deficit	mm	209	181	132	234	199	149	254	310	235	398	399	277	530
Start of field operations (Tsum200)	Day	51	43	35	52	41	33	51	37	29	47	29	21	42
Days above field capacity	Days	49	45	39	52	45	37	54	42	35	50	40	31	51
Agricultural drought: SPEI_6 <-1.5	Prop. of time	0.07	0.14	0.07	0.22	0.16	0.08	0.26	0.19	0.09	0.30	0.30	0.14	0.40
Agricultural drought: SPI_3 <-1.5	Prop. of time	0.07	0.09	0.06	0.13	0.10	0.07	0.16	0.10	0.07	0.16	0.14	0.08	0.22
Crop growth duration	Days	246	204	189	230	200	185	231	194	180	215	182	168	198
Frost days	Days/year	49	36	27	45	34	24	46	28	19	38	17	9	29
Accumulated frost	°C-days	-108	-78	-105	-57	-74	-106	-50	-60	-87	-40	-36	-67	-19
Sheep parasite danger	Days/year	198	219	206	233	223	204	243	234	218	253	264	236	292
Milk yield heat stress	Days/year	4	13	6	25	15	6	33	24	9	46	57	22	92
Wheat heat stress	% chance	0.1	0.4	0.1	1.8	0.5	0.1	2.9	1.9	0.2	6.0	6.9	0.7	25.2
Wales														
Start of growing season	Day	86	84	81	87	81	74	87	78	69	87	74	65	84
Growing season length	Days	245	249	245	253	254	245	263	259	247	271	265	251	278
Growing degree days	°C-days	1555	1601	1569	1633	1670	1593	1748	1764	1636	1898	1847	1680	2022
Potential soil moisture deficit	mm	114	119	113	127	127	112	146	137	112	171	150	115	196
Start of field operations (Tsum200)	Day	50	49	47	51	47	43	51	44	38	51	41	34	50
Days above field capacity	Days	98	97	95	98	95	92	99	94	88	99	92	86	98
Agricultural drought: SPEI_6 <-1.5	Prop. of time	0.07	0.07	0.06	0.08	0.08	0.06	0.11	0.10	0.06	0.16	0.12	0.06	0.19
Agricultural drought: SPI_3 <-1.5	Prop. of time	0.06	0.07	0.06	0.08	0.08	0.06	0.09	0.08	0.06	0.11	0.09	0.06	0.13
Crop growth duration	Days	245	238	233	243	226	216	238	215	202	231	204	190	226
Frost days	Days/year	45	43	42	46	41	37	45	37	31	43	34	27	41
Accumulated frost	°C-days	-101	-102	-108	-97	-95	-107	-85	-85	-103	-69	-75	-98	-56
Sheep parasite danger	Days/year	191	194	191	197	199	193	206	207	196	218	213	201	227
Milk yield heat stress	Days/year	1	2	2	2	2	2	4	3	2	6	5	2	9
Wheat heat stress	% chance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3 (continued)

		1981–2010	RCP2.6						RCP8.5					
			2050s			2080s			2050s			2080s		
			median	low	high	median	low	high	median	low	high	median	low	high
Scotland														
Start of growing season	Day	102	101	99	103	98	93	103	96	89	102	93	85	101
Growing season length	Days	215	218	215	222	223	215	231	229	218	241	234	221	248
Growing degree days	°C-days	1232	1270	1244	1297	1324	1264	1390	1404	1301	1516	1467	1336	1611
Potential soil moisture deficit	mm	120	122	118	126	125	116	136	130	114	148	137	115	163
Start of field operations (Tsum200)	Day	65	63	60	65	60	54	66	56	48	66	53	43	64
Days above field capacity	Days	95	94	93	96	94	90	97	93	87	98	91	85	98
Agricultural drought: $SPEI\_6 < -1.5$	Prop. of time	0.06	0.07	0.06	0.07	0.07	0.06	0.09	0.08	0.05	0.10	0.09	0.05	0.13
Agricultural drought: $SPI\_3 < -1.5$	Prop. of time	0.07	0.06	0.06	0.07	0.06	0.05	0.08	0.07	0.05	0.08	0.07	0.05	0.09
Crop growth duration	Days	223	214	207	219	200	188	213	192	178	208	179	167	201
Frost days	Days/year	65	62	59	65	58	52	64	53	44	63	49	39	60
Accumulated frost	°C-days	−156	−155	−165	−146	−145	−164	−129	−131	−160	−107	−119	−155	−91
Sheep parasite danger	Days/year	159	163	160	166	167	161	174	174	164	185	180	168	193
Milk yield heat stress	Days/year	0	0	0	0	1	0	1	1	0	2	1	0	3
Wheat heat stress	% chance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Northern Ireland														
Start of growing season	Day	90	88	86	91	85	79	91	82	74	89	79	68	88
Growing season length	Days	237	241	237	245	247	238	256	253	241	266	258	245	273
Growing degree days	°C-days	1405	1446	1418	1475	1508	1441	1579	1592	1480	1713	1661	1517	1812
Potential soil moisture deficit	mm	87	90	86	95	95	84	108	100	83	121	107	86	137
Start of field operations (Tsum200)	Day	49	48	46	50	46	42	50	44	38	50	41	34	49
Days above field capacity	Days	107	105	103	107	105	101	109	103	97	109	101	94	108
Agricultural drought: $SPEI\_6 < -1.5$	Prop. of time	0.07	0.07	0.06	0.08	0.08	0.06	0.11	0.09	0.05	0.15	0.11	0.06	0.17
Agricultural drought: $SPI\_3 < -1.5$	Prop. of time	0.07	0.07	0.06	0.08	0.07	0.06	0.09	0.08	0.06	0.11	0.09	0.06	0.12
Crop growth duration	Days	239	231	225	236	218	208	231	210	198	226	199	186	221
Frost days	Days/year	45	43	40	45	40	35	45	36	29	43	32	25	41
Accumulated frost	°C-days	−84	−86	−93	−80	−80	−92	−71	−71	−88	−58	−63	−84	−47
Sheep parasite danger	Days/year	178	181	178	185	186	180	193	194	183	204	199	187	212
Milk yield heat stress	Days/year	0	0	0	1	1	0	1	1	0	2	1	1	3
Wheat heat stress	% chance	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

2020), after which they become more likely in eastern England by the 2050s and across most of the south and east by the 2080s.

Figures 4 and 5 compare the climate change trend in the mean with annual variability, and this gives an indication of changes in the future occurrence of 'extreme' years—although precise quantification depends of course on the definition of 'extreme'. However, climate change also affects year to year variability around the mean for some indicators (Figs. 8 and 9). This occurs even though the delta approach used here to construct climate scenarios does not significantly affect year to year variability in weather, because most of the indicators are based on exceedance of some threshold. Variability in the start of the growing season and growing season length increases slightly, and there is a relatively greater increase in the variability in growing degree days. In contrast, the variability in the start of field operations reduces over time—it becomes more consistent—but there is little change in the average potential soil moisture deficit or number of days with wet soils. Drought variability increases as droughts become more frequent, then decreases—particularly for SPEI—as droughts begin to occur in most years. There is little change in the variability in frost days, but the variation in accumulated frost reduces as totals become smaller. There is a slight increase in variability in the number of days suitable for sheep parasites, but a greater increase in the year-to-year variability in days with heat stress for dairy cattle.

The plots show that whilst there is a broad agreement of the direction of change in a region for a given indicator, there can be considerable uncertainty in the magnitude of change by the end of the twenty-first century and the rate of change. For the temperature-based indicators, it is generally influenced by how rapidly temperatures increase for a given rate of change in emissions and this is strongly influenced by the sensitivity of the climate system to forcing. This is typically characterised by Equilibrium Climate Sensitivity (ECS), and the latest generations of climate models tend to have higher ECS values than previous generations (Meehl et al. 2020). For the rainfall-based indicators (soil wetness and drought), the uncertainty is largely driven by uncertainty in the magnitude of the change in rainfall which is itself due to differences in the atmospheric dynamic response to forcing between models.

The probabilistic projections combine information from the two global strands—HadGEM3 and CMIP5—and the two strands span different parts of the uncertainty range (see Supplementary Material). The HadGEM3 projections have a greater rate of increase in temperature for a given forcing than the CMIP5 projections (they have a higher ECS), and also tend to generate larger increases in winter rainfall and larger reductions in summer rainfall. The HadGEM3 projections therefore show larger changes in agro-climate indicator—and are therefore at the top of the uncertainty ranges in Figs. 4, 5, and 7—whilst the CMIP5 ensemble tends to show smaller changes.

5 Conclusions and implications for agriculture in the UK

Agriculture in the UK is currently facing a series of challenges, including Brexit (altering not only relationships with European and international markets but also government policy priorities), changes in customer preferences, public and policy perceptions of the role of agriculture in the landscape, and increasing concerns with environmental sustainability and stewardship. This paper shows, using a range of indicators relevant to the UK, that climate change adds materially to these challenges by altering the climatic conditions that farmers and agricultural systems have become accustomed to. The information presented here can be used
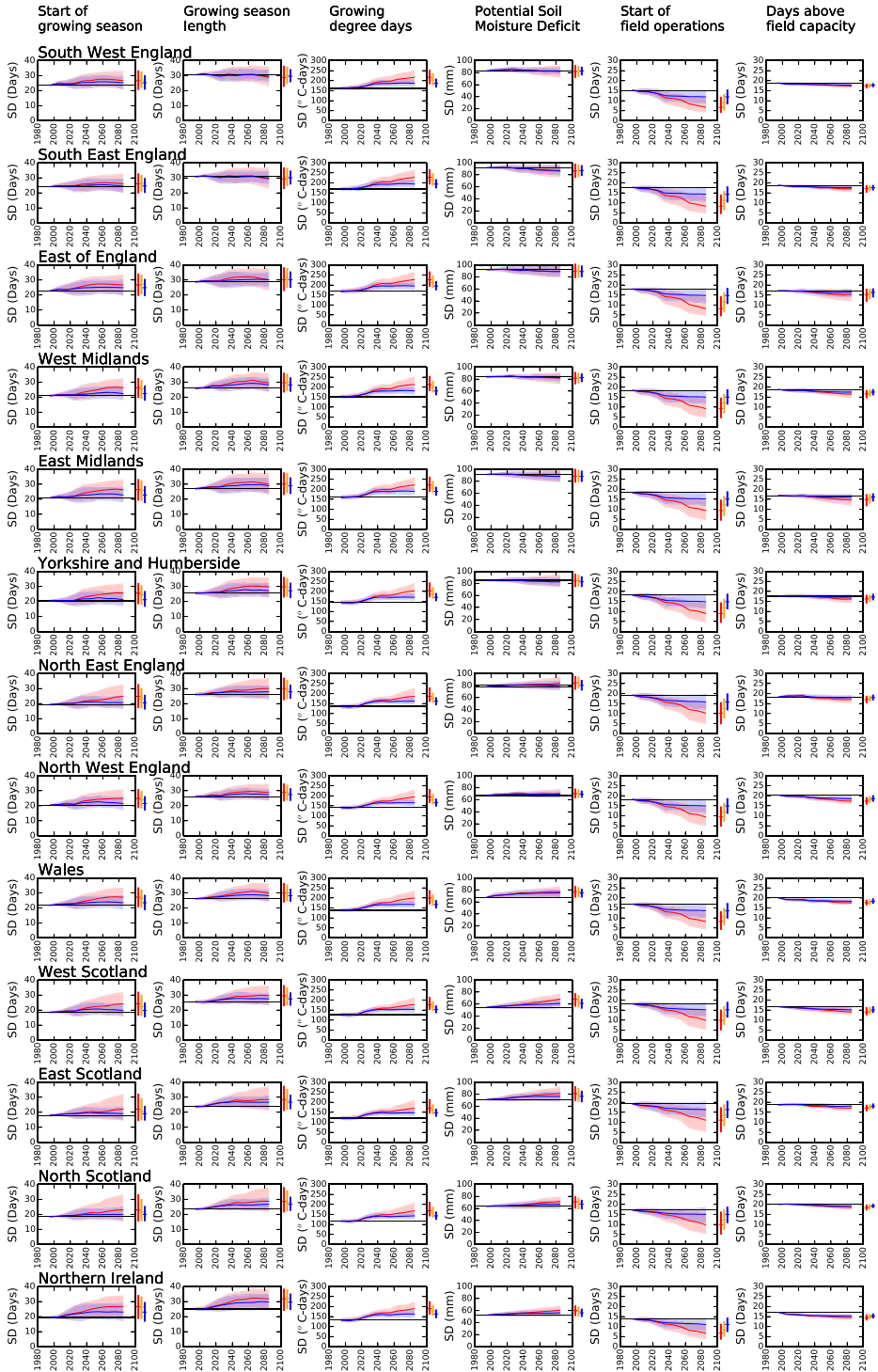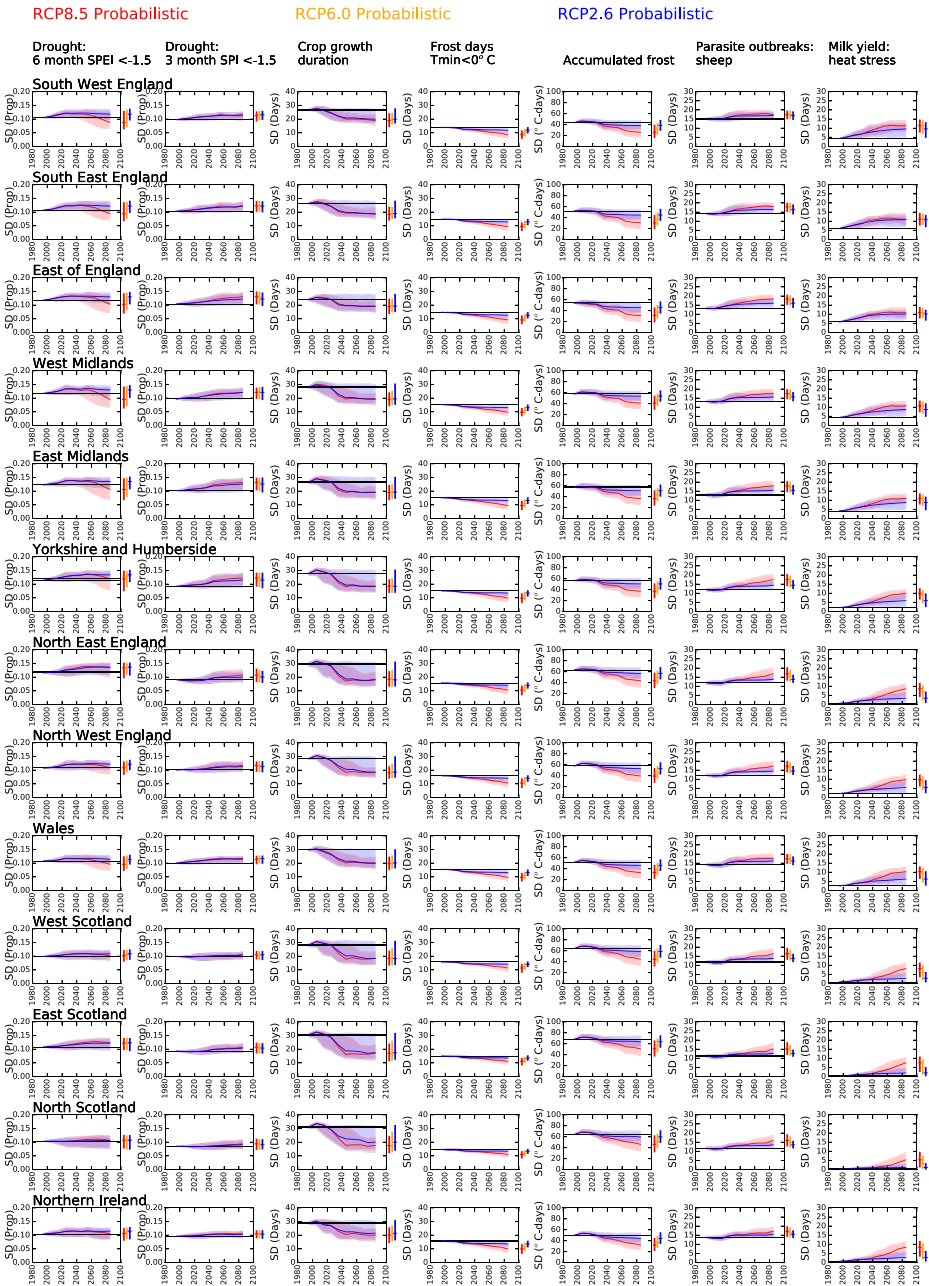
◀ Fig. 8 Standard deviation of the indicators of climate resource by region: probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The standard deviation over 30 years is plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high')

Fig. 9 Standard deviation of the indicators of climate hazard by region: probabilistic projections, RCP2.6, RCP6.0, and RCP8.5. The standard deviation over 30 years is plotted at the central year of the 30-year period, and the plots show the median plus the 10th to 90th percentile ranges ('low' to 'high')

to inform high-level assessments of potential changes to agriculture in the UK and implications for adaptation and mitigation strategy. It provides the context for more tailored sector- or place-focused adaptation and resilience planning—for example based around thresholds for critical change—and highlights areas for further investigation. Although there are differences in the detail of the climate projections and indicators used and spatial scale, the results here are broadly qualitatively consistent with those of previous studies of agro-climatic indicators in the UK—but they cover a wider range of indicators than these previous studies.

There are two major caveats with the approach used. First, the delta method used to construct future climates preserves the current year-to-year variability in climate (although variability in the indicators can change) and therefore does not incorporate the extra potential effects of changes in climatic variability from year to year or day to day. Second, the approach uses generalised indicators which are proxies for agricultural impacts, rather than attempt to estimate actual impacts using site- and crop-specific metrics, and most of these indicators characterise changes in the mean rather than the occurrence of extremes. In practice, adverse impacts in any 1 year may be very dependent on the precise timing or characteristics of extreme weather events. The projected effects of climate change are here characterised by changes in the multi-year mean (with the exception of the wheat heat stress indicator), but other threshold-based indicators representing potential changes in 'extreme' years can be readily calculated from the underlying annual values once critical thresholds are defined.

The results show that there will be substantial changes in the climate resource and hazard across the UK during the twenty-first century if emissions continue to follow a high trajectory, and there will still be some changes if emissions reduce to achieve international climate policy targets. Future climate conditions for agriculture will be very different from current conditions. Growing seasons will lengthen, crop growth will be accelerated, and both drought and heat risks will increase—although damaging high temperatures for wheat are unlikely to become significant until the 2050s. Soils will generally become drier in autumn (despite increases in autumn rainfall), although there will be less change in winter and spring. Opportunities will arise for new crops. Some changes are broadly consistent across the UK, but others are more geographically variable. Increases in heat, drought, and soil moisture deficit risks are greatest in the south and east of England, but the greatest increase in sheep parasite danger is in the west. For most of the indicators, the trend over the twenty-first century is small compared with year-to-year variability, but the underlying trends will alter the frequency of low and high extremes.

The link between agro-climate indicators and future yields, however, varies between crop types and management practices. Most significantly, the yield of C3 crops—which include wheat, barley, and grass—is affected by atmospheric CO_2 concentration, and this may offset the adverse effects of increased water stress (as shown for example in crop modelling studies by Semenov (2009), Yawson et al. (2016), Qi et al. (2018), Ritchie et al. (2019), and Harkness et al. (2020)). Changes in CO_2 concentration have little effect on the productivity of C4 plants—including maize—so they will be more directly affected by changes in climate. Reductions in crop development times may reduce yields, but at the same time may mean that crops mature before being exposed to drought or heat stress (Semenov 2009; Harkness et al. 2020). Changes in climate and CO_2 concentrations will also affect the growth of weeds. Meanwhile, farmers will plant new crops and cultivars in response to changing conditions.

Whilst the effects of changes in climate resource and hazard on actual productivity are therefore difficult to quantify, it is clear that climate change will tend to increase the frequency of three of the

most challenging weather events affecting crop growth and livestock welfare and productivity—heat stress, drought, and (not explicitly considered here; see Kay et al. 2014) flood. Heat stress increases most significantly in southern England, whilst drought stress increases more widely across all but the western parts of the UK. On average, water-logging may become less likely in the future, improving access to land, but the changes will be greatest in autumn rather than spring and wet years with wet soils in late spring will still occur. This general increase in the likelihood of challenging conditions through the year will not only affect actual productivity, but will also affect farmer decisions about what to plant and what infrastructure is needed.

Measures to enhance resilience to change in the mean and the likelihood of extreme events in the agricultural sector operate at two levels. At the farm level, the farmer has three broad categories of measure: (i) use new crops, cultivars, varieties or breeds, (ii) change practices, or (iii) diversify. The farmer may chose, for example, to plant a crop or a cultivar, or use a breed of livestock, that is less vulnerable to drought or heat stress. This may involve changing from one broad type of farming to another, for example from arable to livestock, but this may involve substantial transaction costs relating to machinery, storage, labour, and skills. Changing practices may involve altering the timing of actions, using irrigation, or using seasonal forecasts to inform planting decisions. Diversification involves broadening the range of activities to lessen the farm-scale effects of adverse conditions (Gaudin et al. 2015; Urruty et al. 2016; Dardonville et al. 2020).

At the agricultural system level, there are several potential categories of measure. One is to develop new cultivars or varieties that are suitable for changed climatic conditions, and another is develop new practices appropriate for hotter and drier climates—for example improved irrigation or livestock housing. Improvements in seasonal weather forecasting might help farmers make planting and management decisions, given an increased risk of damaging events during the growing season.

Farm and system level measures to enhance resilience, however, need to be embedded within an enabling policy framework. Following its departure from the European Union and its Common Agricultural Policy, the UK government is developing a new policy approach to agriculture. A new Agriculture Bill was submitted to Parliament in January 2020, which seeks to support farming and the rural economy and landscape. It places great emphasis on Environmental Land Management, aiming to refocus public support to encourage environmentally sustainable behaviours and practices. However, whilst climate change is widely cited in policy documents (e.g. Defra 2020b), the discussion is limited to climate mitigation and the reduction of greenhouse gas emissions. In principle, the mechanisms currently proposed to enhance farm resilience (through grants for investment) could be used to adapt to a changing climate, although this is not explicitly mentioned.

All these farm and system scale measures to enhance resilience need to be informed by projections of how agricultural conditions may change in the future, and this paper presents a consistent set of projections of a range of relevant indicators using the latest climate projections. The general direction of change is clear—with the notable exception of days with wet soils—but the rate and magnitude of change is uncertain. To the 2040s, at least the projected changes do not depend on assumptions about future emissions, and the range in possible changes in a place is driven by uncertainty in precisely how climate changes across the UK in response to increases in greenhouse gas emissions. For the temperature-based indicators, this largely reflects uncertainty in the overall sensitivity of the climate system to change in forcing, whilst for the rainfall-based indicators, it reflects uncertainty in changes in weather patterns bringing rainfall to the UK. This uncertainty is important because it implies that measures to enhance resilience need explicitly to take into account uncertainty in how climate will change: measures that can cope with a central estimate of change in mean or variability may not be sufficient to cope with projected plausible large changes.

Code availability The analysis used custom code, which can be made available on request.

Author contributions NWA conceived the study, AF constructed the climate scenarios, and NWA and AF wrote the paper.

Data availability Regional and national data are provided in Supplementary Material.

Declarations

Conflict of interest The authors declare no competing interests.

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